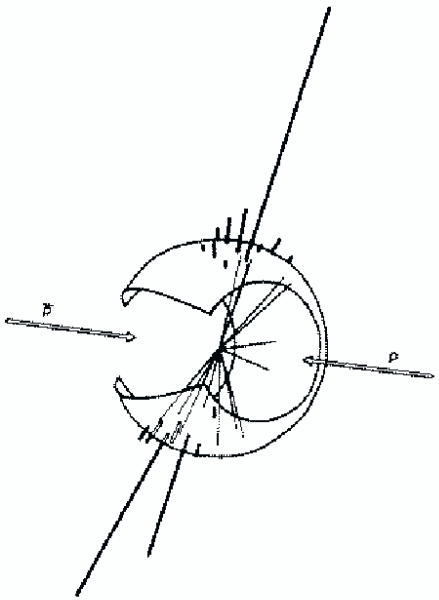
Modification of the jet properties at the Relativistic Heavy Ion Collider



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PHENIX

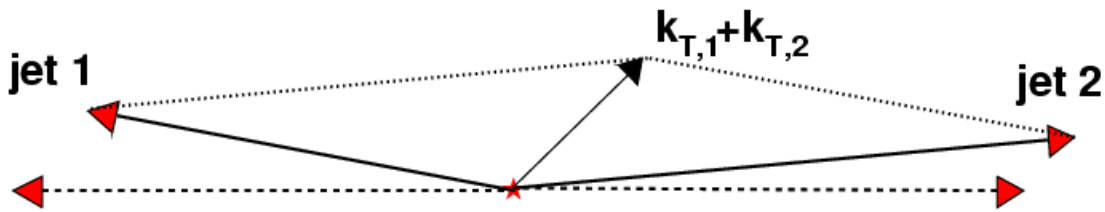
QCD in Heavy Ion collisions

Two particles azimuthal correlations in pp, dAu and AuAu

- nuclear modification of jet properties:
  - Intrisic momentum k_T
  - Jet transverse fragmentation momentum j_T
  - Parton distribution function
  - Fragmentation function

Hard scattering

Hard scattering in transverse plane



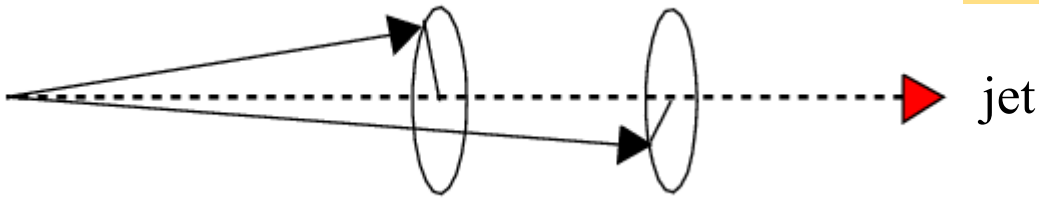
Point-like partons $\Rightarrow$ elastic scattering $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{0}$

Partons have intrinsic transverse momentum $\boldsymbol{k_T}$ $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{k}_{T,1} + \vec{k}_{T,2}$

Jet Fragmentation (width of the jet cone)

Partons have to materialize (fragment) in colorless world

$\vec{j}_T$ = jet fragmentation transverse momentum



j_T and k_T are 2D vectors. We measure the mean value of its projection into the transverse plane $\langle|j_{Ty}|\rangle$ and $\langle|k_{Ty}|\rangle$.

$$\langle|\, k_{Ty}\,|\rangle = \sqrt{\frac{2}{\pi}}\sqrt{\langle k^2{}_T\rangle}$$

$\langle|j_{Ty}|\rangle$ is an important jet parameter. It's constant value independent on fragment's p_T is characteristic of jet fragmentation (j_T-scaling).

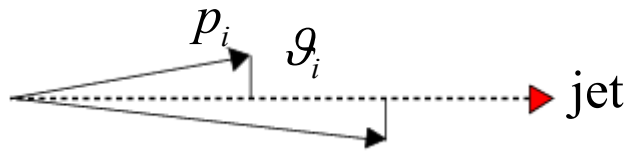
$\langle|k_{Ty}|\rangle$ (intrinsic + NLO radiative corrections) carries the information on the parton interaction with QCD medium.

$$\langle k_\perp{}^2\rangle_{AA} = \langle k_\perp{}^2\rangle_{vac} + \langle k_\perp{}^2\rangle_{IS\ nucl} + \langle k_\perp{}^2\rangle_{FS\ nucl}$$

p+p p+A A+A

Fragmentation Function (distribution of parton momentum among fragments)

In Principle



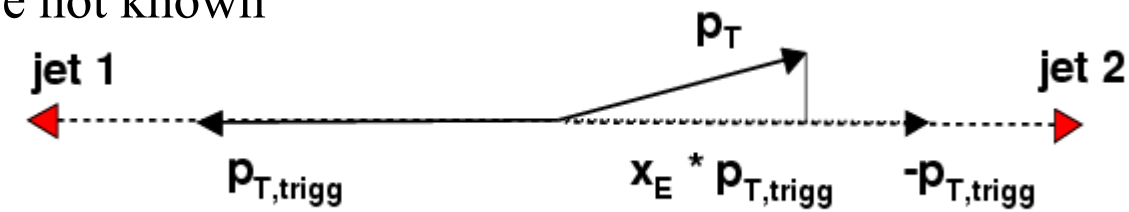
$$\vec{p}_{parton} = \sum_i \vec{p}_i \qquad |\vec{p}_{parton}| = \sum_i |\vec{p}_i| \cos(\vartheta_i)$$

$$z_i = \frac{|\vec{p}_i| \cos(\vartheta_i)}{|\vec{p}_{parton}|} \qquad \sum_i z_i = 1$$

Fragmentation function $D(z) \propto e^{-z/\langle z \rangle}$

In Practice parton momenta are not known

$$x_E = -\frac{\vec{p}_T \cdot \vec{p}_{Ttrigg}}{|\vec{p}_{Ttrigg}|^2}$$

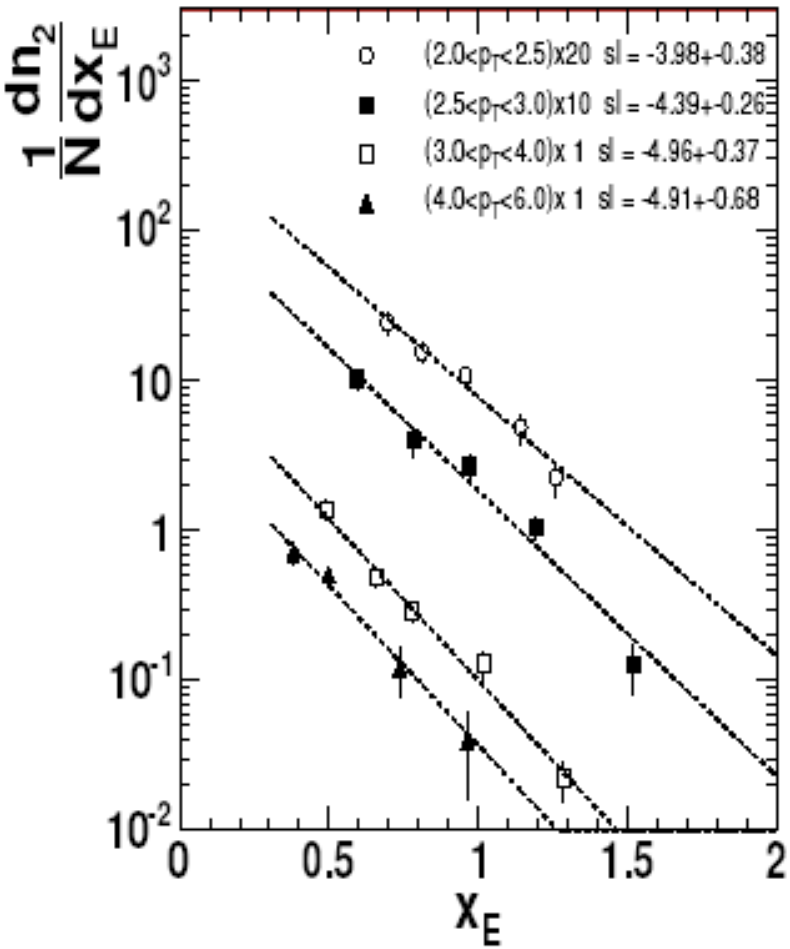


$$x_E z_{trigg} = \frac{p_T \cos(\Delta\varphi)}{p_{parton}} = z$$

$\Rightarrow$ Simple relation $\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$

x_E in pp collisions

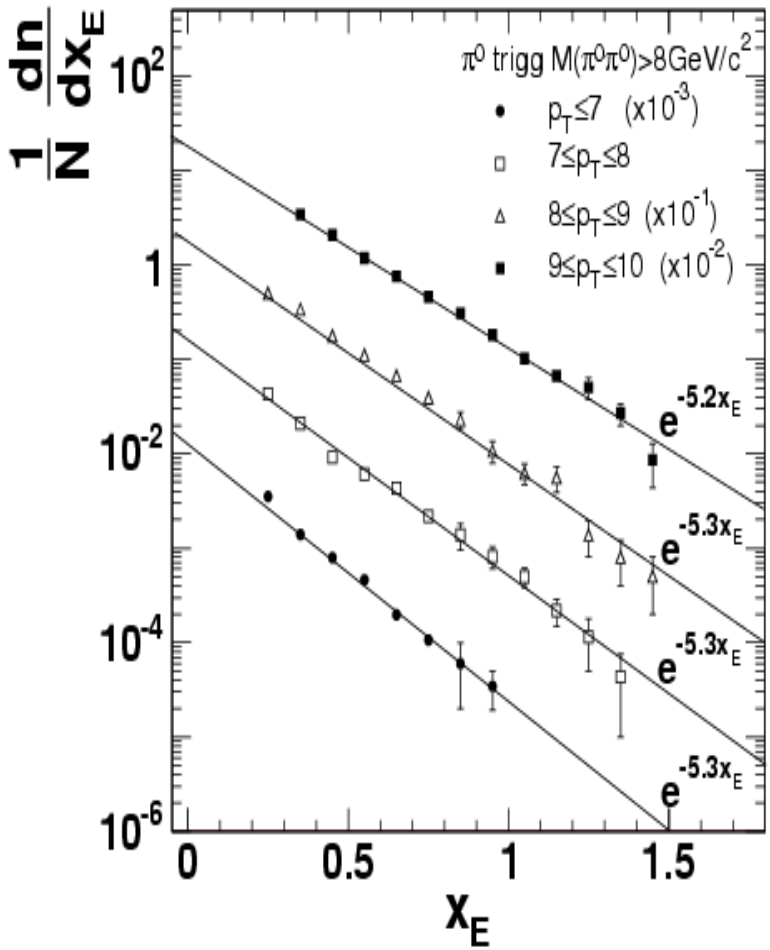
PHENIX preliminary



$1/\langle x_E \rangle \approx -4$ to -5

CCOR (ISR) $\sqrt{s}$ = 63 GeV

see A.L.S. Angelis, Nucl Phys B209 (1982)



$1/\langle x_E \rangle \approx -5.3$

⟨z⟩ extracted from pp data

We measured x_E and

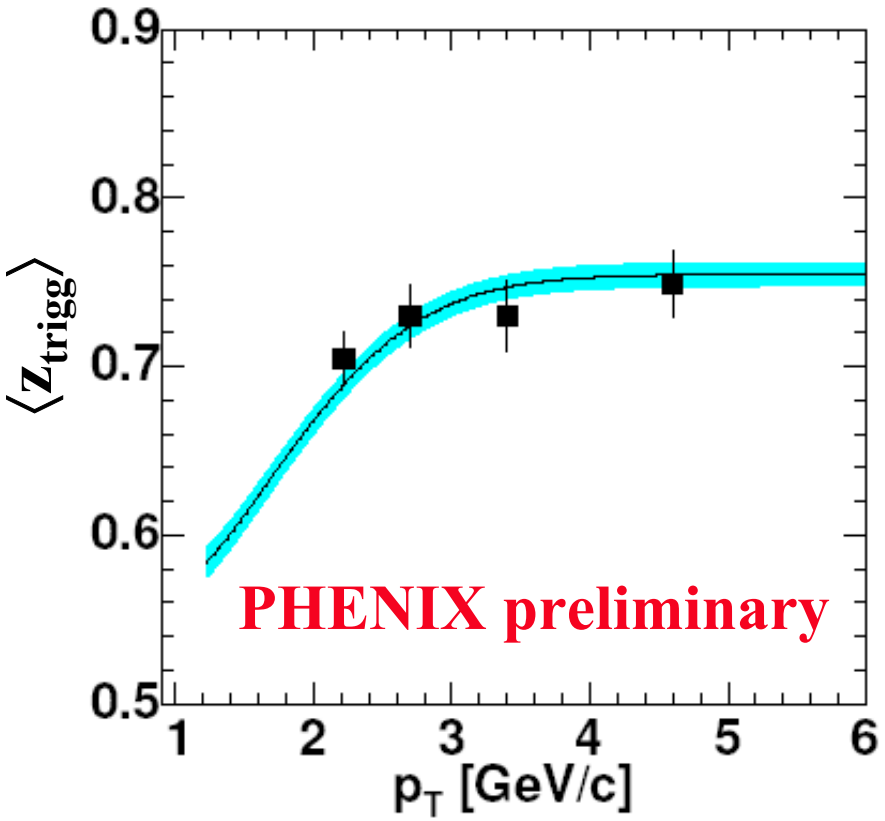
$$\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$$

$x_{Ttrigg}=2.p_{Ttrigg}/\sqrt{s}$

$$\langle z_{trigg} \rangle \propto \int_{x_{Ttrigg}}^{1} z \cdot e^{-z/\langle z \rangle} f_q(p_T/z) \cdot z^{-2} dz$$

Only one unknown variable ⟨z⟩ ⇒ iterative solution

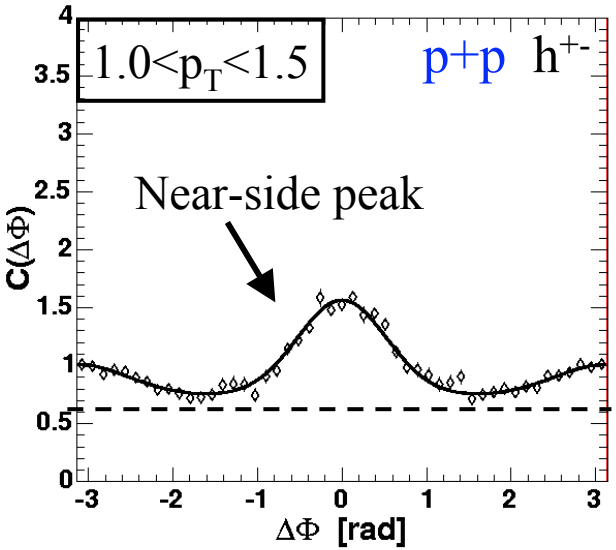
FFn $D(z)$ final state parton distrib. extracted from PHENIX $p+p \rightarrow \pi^0+X$

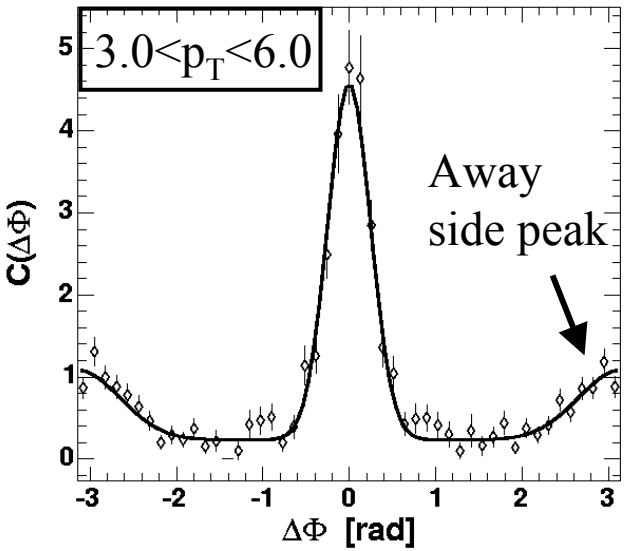


Slope of the fragmentation function in p+p collisions at √s=200 GeV

$$\frac{1}{\langle z \rangle} = 6.16 \pm 0.32$$

pp and dAu correlation functions



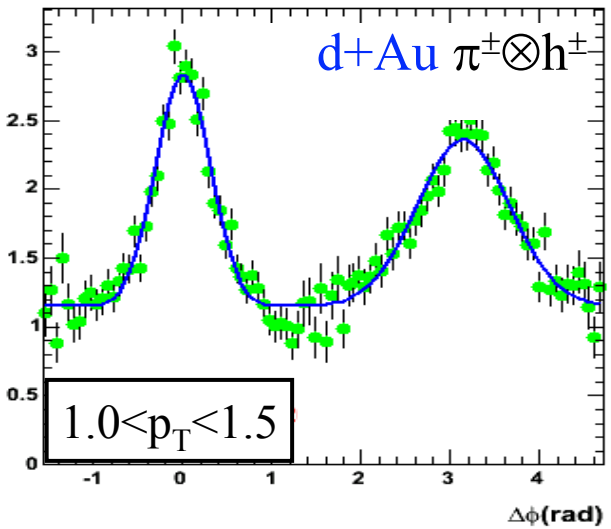


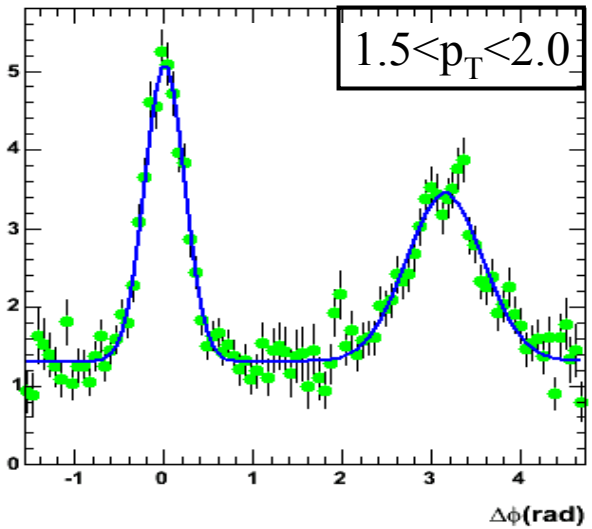
Fixed correlation:

both p_{Ttrigg} and p_{Tassoc} are in the same range

Assorted correlation:

p_{Ttrigg} and p_{Tassoc} different





$5.0 < p_{Ttrigg} < 16.0$ GeV/c

Jet function assumed to be Gaussian

$$C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$$

→ Fit = const + Gauss(0)+Gauss(±π)

σ_N, σ_A , $\langle|j_{Ty}|\rangle$, $\langle|k_{Ty}|\rangle$ relations

Knowing σ_N and σ_A it is straightforward to extract $\langle|j_{Ty}|\rangle$ and $\langle z_{trigg}\rangle$ $\langle|k_{Ty}|\rangle$

In the high-p_T limit ($p_T >> \langle|j_{Ty}|\rangle$ and $p_T >> \langle|k_{Ty}|\rangle$)

$$\left\langle \left| j_{\perp y} \right| \right\rangle = \left\langle p_{\perp} \right\rangle \sin \frac{\sigma_N}{\sqrt{\pi}}$$

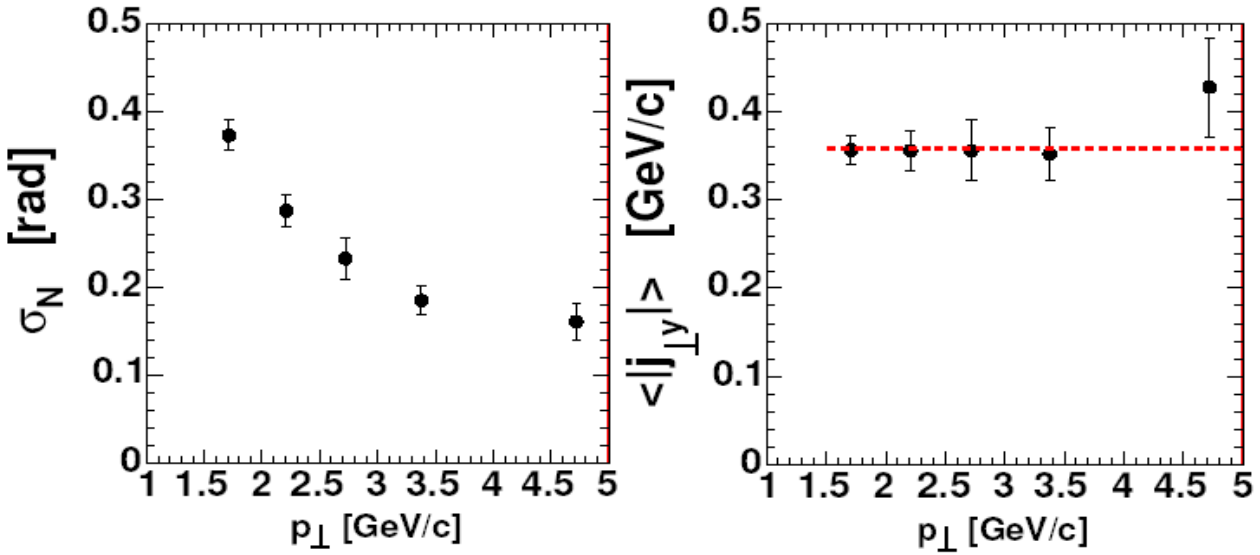
$$\left\langle \left| k_{Ty} \right| \right\rangle \approx \left\langle p_T \right\rangle \sqrt{\sigma_A^2 - \sigma_N^2}$$

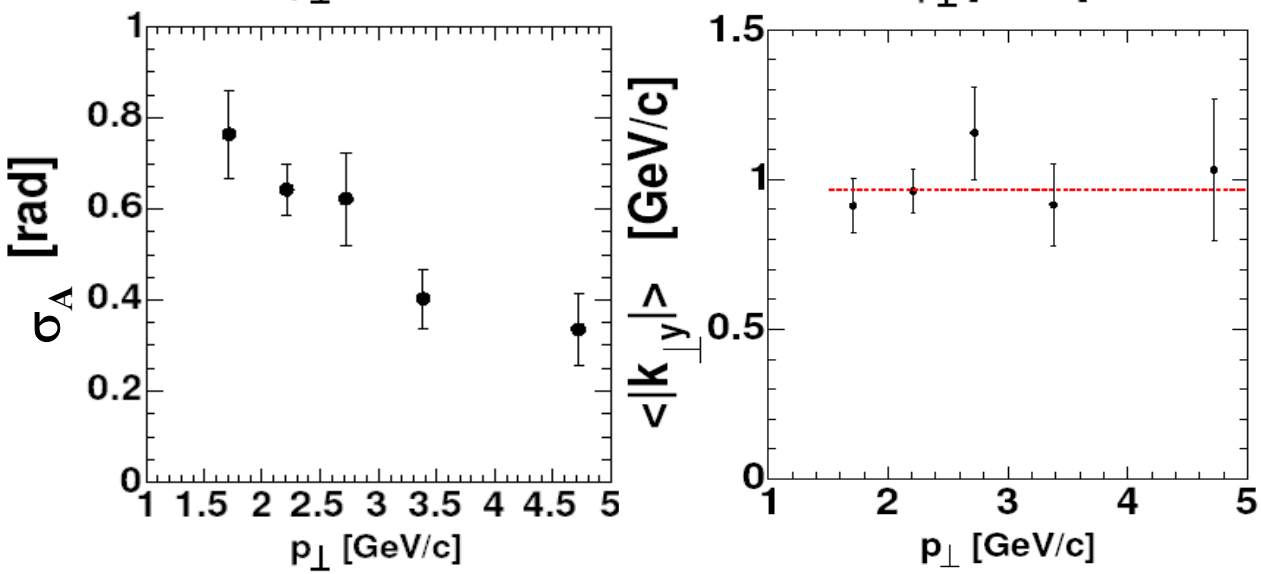
However, inspired by Feynman, Field, Fox and Tannenbaum (see *Phys. Lett. 97B (1980) 163*) we derived more accurate equation

$$\langle z_{trigg} \rangle \langle | k_{Ty} | \rangle = \frac{\langle p_T \rangle}{\sqrt{2}\, x_h} \sqrt{\sin^2 \sqrt{\frac{2}{\pi}} \sigma_A - (1 + x^2{}_h) \sin^2 \frac{\sigma_N}{\sqrt{\pi}}}$$

$x_h = p_{T,assoc} / p_{T,trigg}$

$\sigma_N, \sigma_A \rightarrow \langle |j_{Ty}| \rangle, \langle |k_{Ty}| \rangle$ in pp data





$$\langle k_\perp^{\,2} \rangle_{pp} = \langle k_\perp^{\,2} \rangle_{vac}$$

PHENIX preliminary

$\langle |j_{Ty}| \rangle = 359 \pm 11$ MeV/c

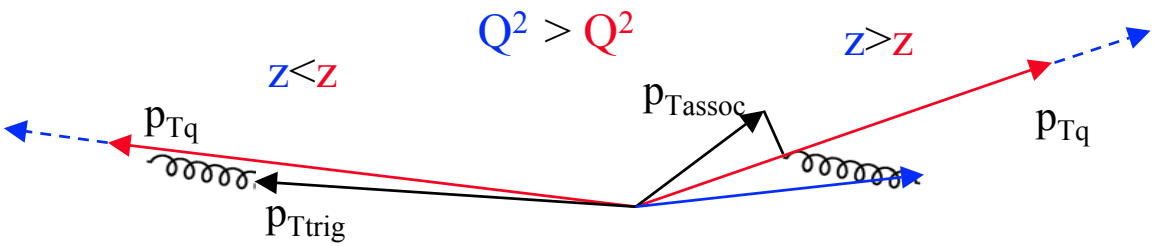
$\langle |k_{Ty}| \rangle = 964 \pm 49$ MeV/c

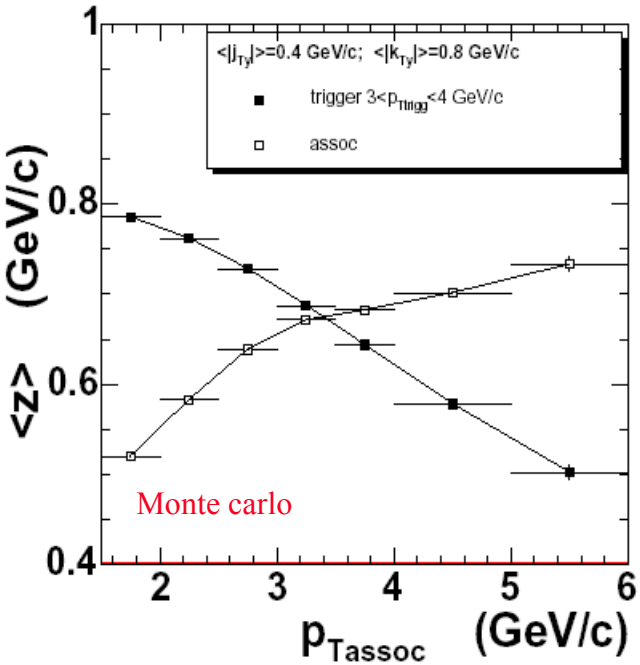
Both $\langle |j_{Ty}| \rangle$ and $\langle |k_{Ty}| \rangle$ in very good agreement with previous measurements:

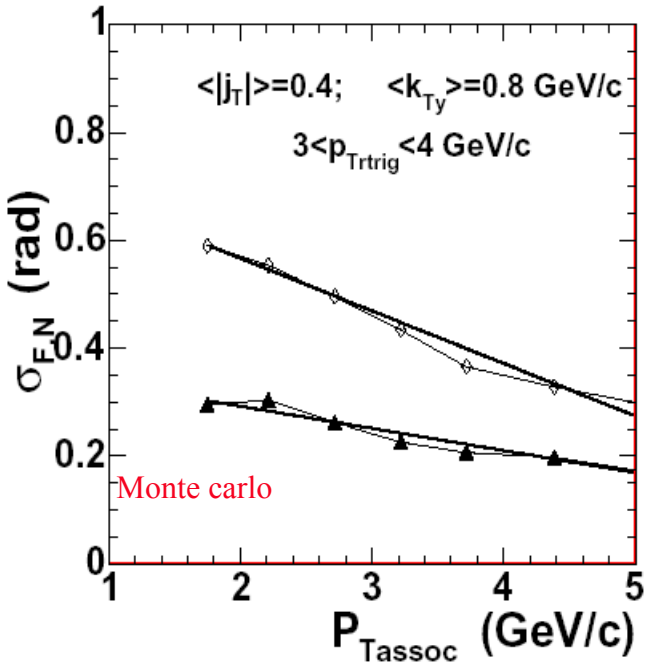
PLB97 (1980)163

PRD 59 (1999) 074007

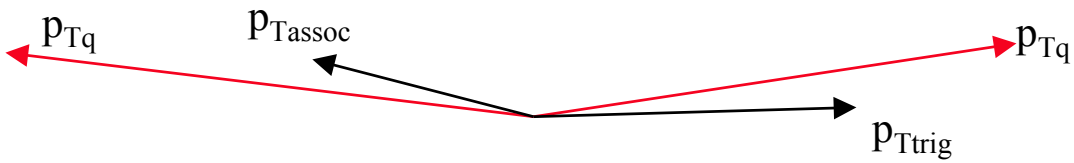
Di-jet fragmentation



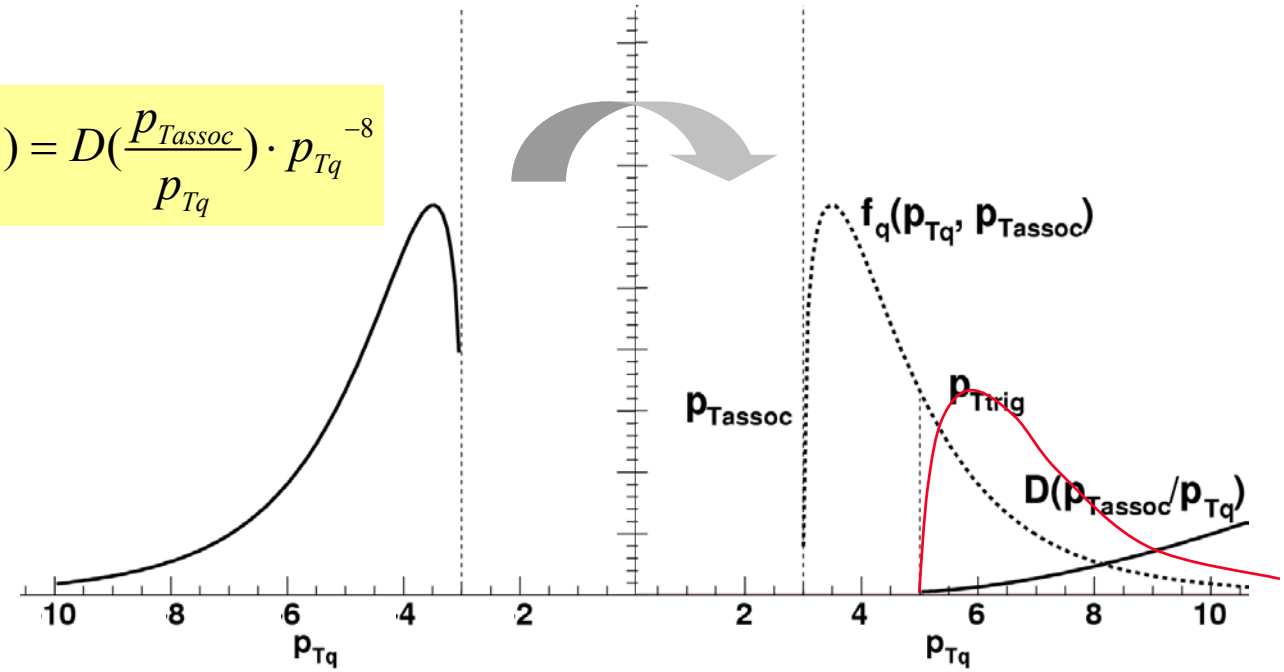




"wave function collapse"



$$f_q(p_{Tq}, p_{Tassoc}) = D(\frac{p_{Tassoc}}{p_{Tq}}) \cdot p_{Tq}^{-8}$$



For fixed pT correlation the parton distribution function is almost unaffected by the condition of having fragment on the opposite side.

kT-smearing

Associated parton distribution $f_a = kT \otimes f_t$ and the final formula for invariant cross section is

$$\frac{1}{p_t}\frac{d^2\sigma}{dp_t dp_a} = \frac{1}{p_t}\int_{p_t}^{\sqrt{s}/2} dq_t \cdot D(\frac{p_t}{q_t}) \cdot \frac{1}{q_t}\int_{p_a}^{\sqrt{s}/2} dq_a \cdot C_{bb}(q_a - q_t, \langle k_T^2 \rangle) \cdot f(q_a) \cdot D(\frac{p_a}{q_a})$$

Correlation fcn between b2b parotns gaussian for kt>0 or delta function for kT=0

$$q_t \to \frac{p_t}{z_t}$$

$$\frac{1}{p_t}\frac{d^2\sigma}{dp_t dp_a} = \frac{1}{p_t}\int_{p_t}^{\sqrt{s}/2} dz_t \cdot D(z_t) \cdot \frac{1}{z_t}\int_{p_a}^{\sqrt{s}/2} dq_a \cdot C_{bb}(q_a - \frac{p_t}{z_t}, \langle k_T^2 \rangle) \cdot f(q_a) \cdot D(\frac{p_a}{q_a})$$

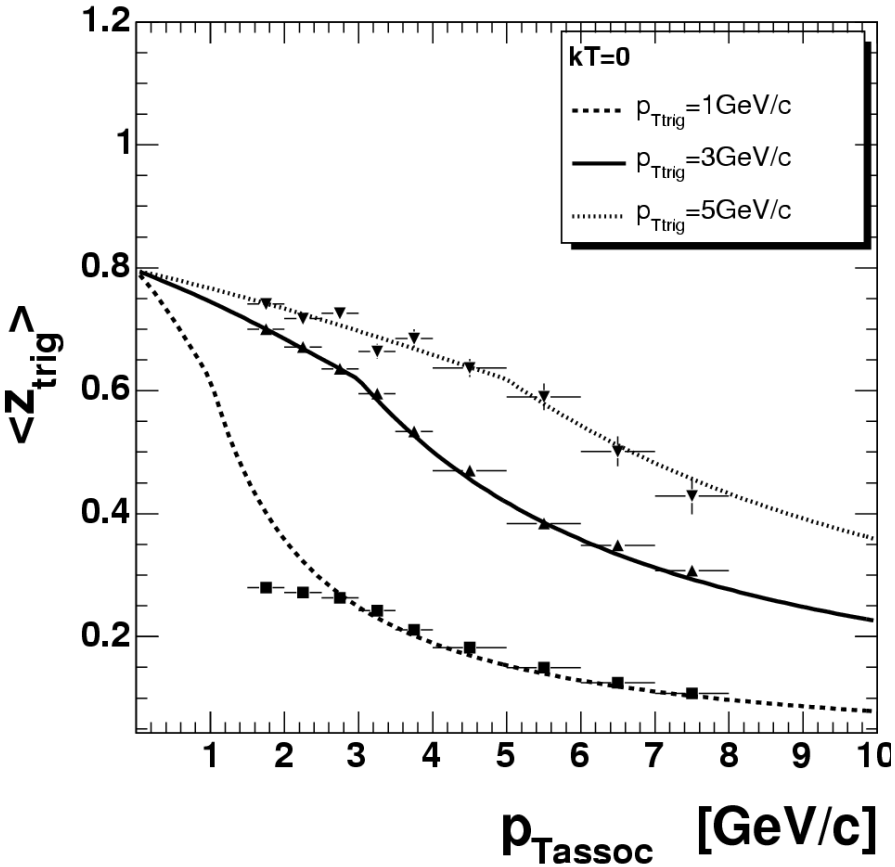
Di-jet mean z

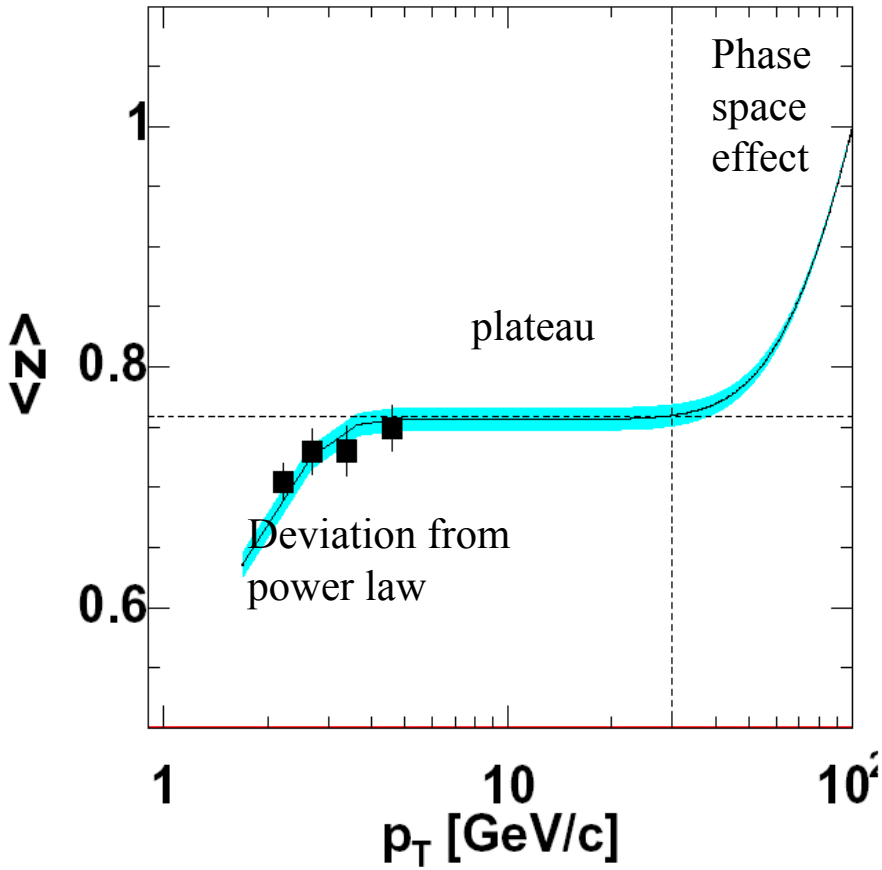
conditional

$$\langle z_t \rangle = \frac{\int_{x_{Tt}}^{p_{Tt}/p_{Ta}} f_q(\frac{p_{Tt}}{z_t}) \cdot D(z_t) \cdot D(\frac{p_{Ta}}{p_{Tt}} z_t) \cdot dz_t}{\int_{x_{Tt}}^{p_{Tt}/p_{Ta}} \frac{1}{z_t} f_q(\frac{p_{Tt}}{z_t}) \cdot D(z_t) \cdot D(\frac{p_{Ta}}{p_{Tt}} z_t) \cdot dz_t}$$

inclusive

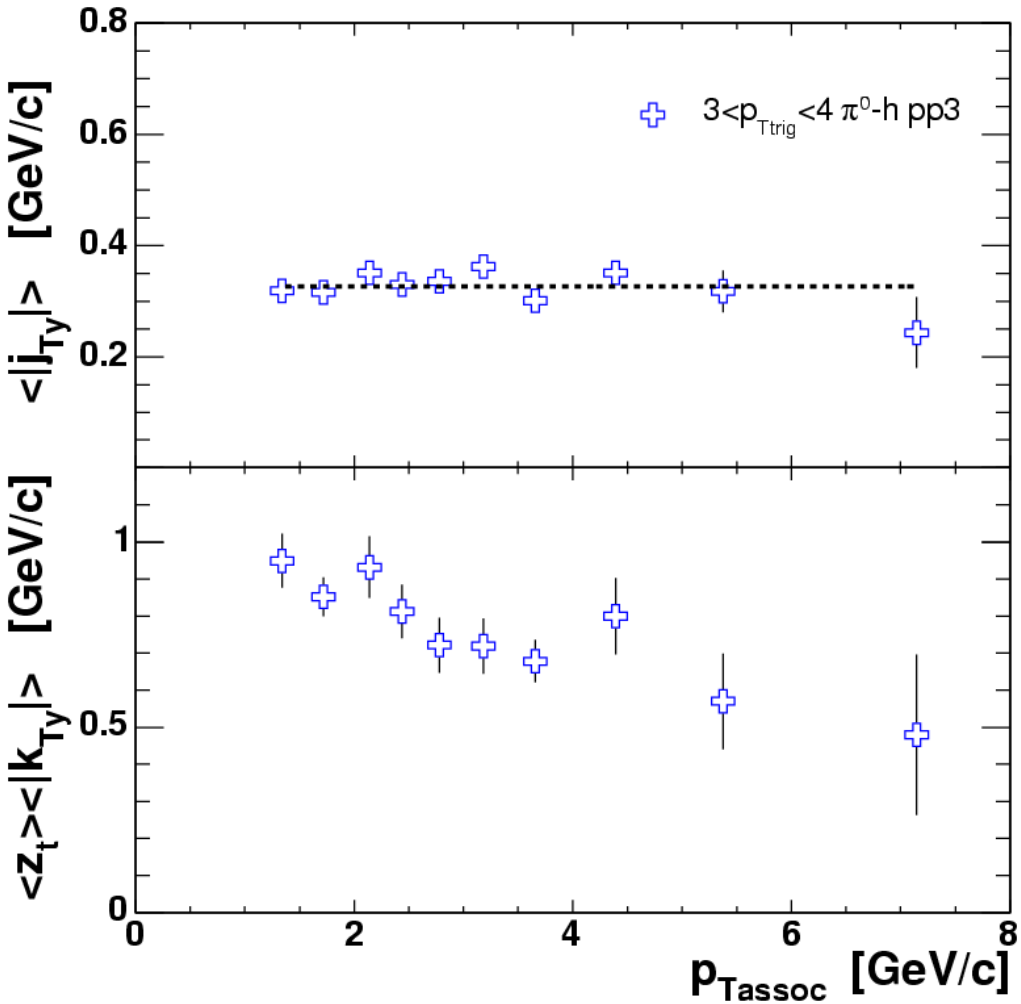
$$\langle z \rangle = \frac{\int_{x_\perp}^{1} z \; z^{-2} \; D(z) \; f_q(p_\perp / z) \; dz}{\int_{x_\perp}^{1} z^{-2} \; D(z) \; f_q(p_\perp / z) \; dz}$$



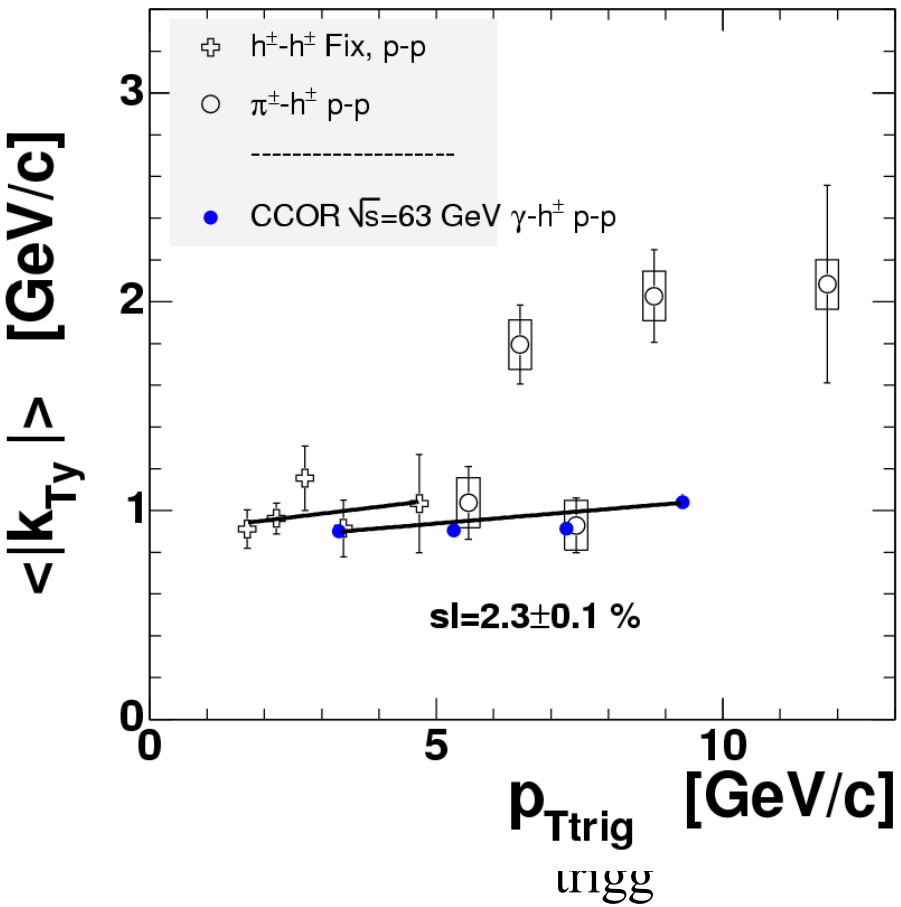


Simulation

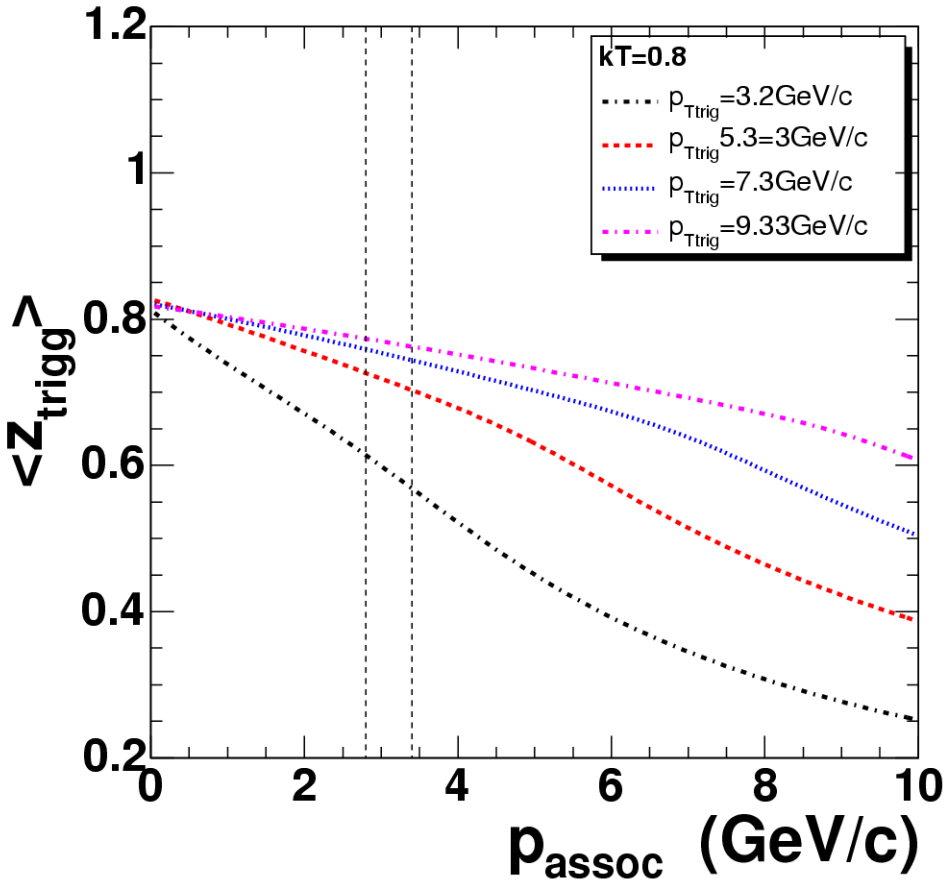
Sorry, I can show only simulation – the final data Phys. Rev. C.



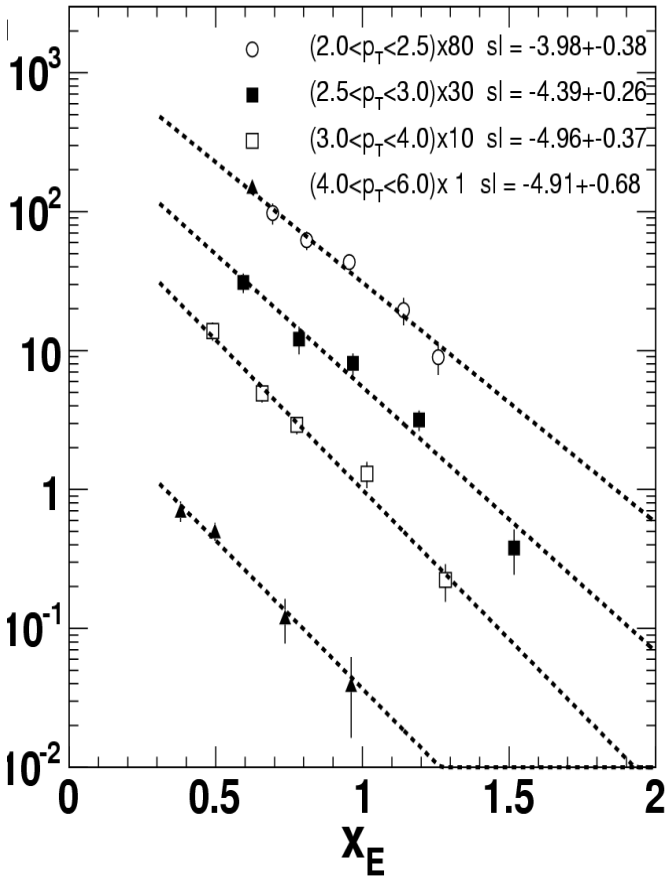
PHENIX/CCOR p_{trigg} slopes



trigg

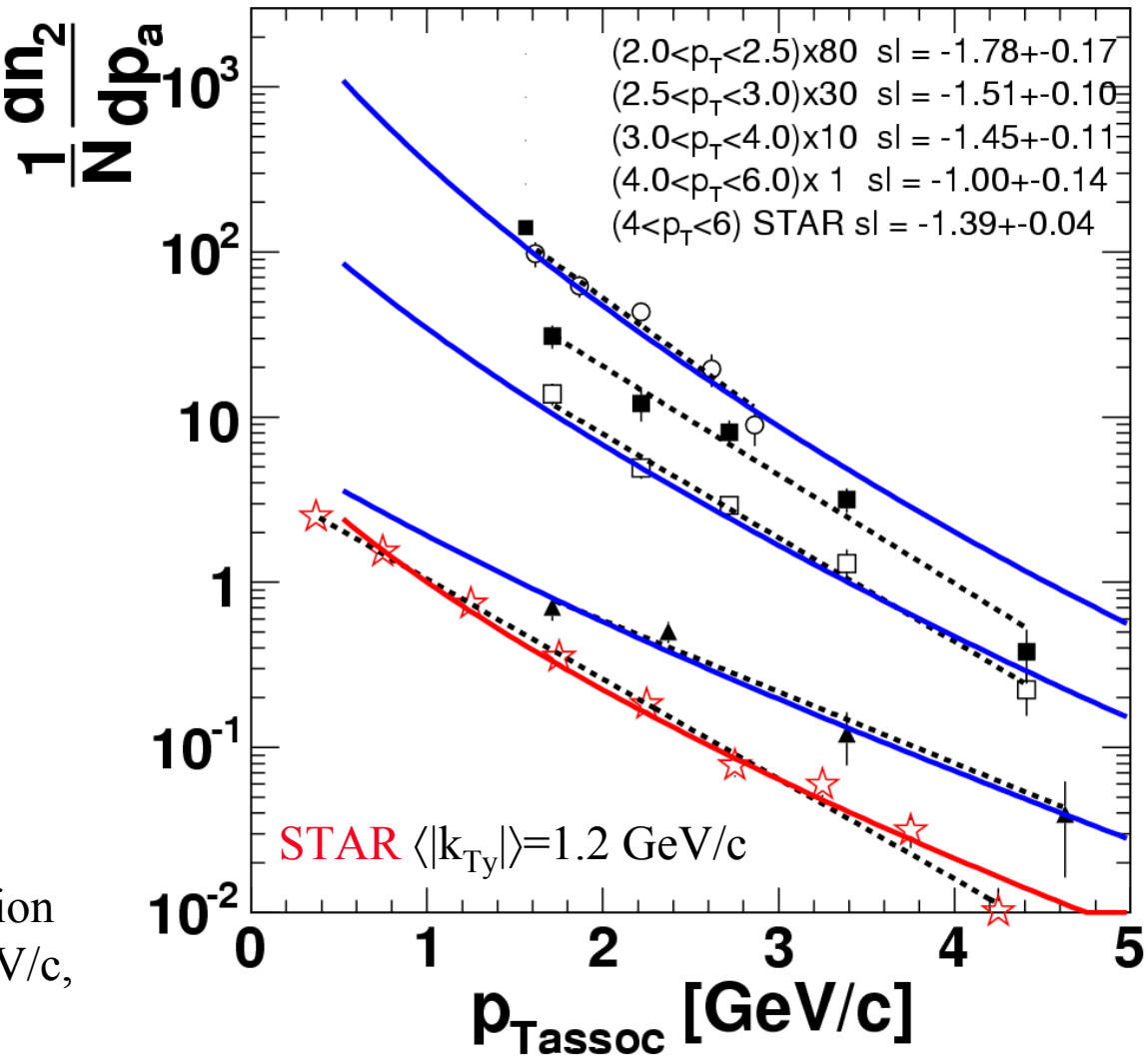


Associated yields – complementary method of $\langle|k_{Ty}|\rangle$ extraction



We can describe all p_{Tassoc} distribution with unique value of $\langle|k_{Ty}|\rangle$=0.9 GeV/c, but not STAR data.

PHENIX $\langle|k_{Ty}|\rangle$=0.9 GeV/c

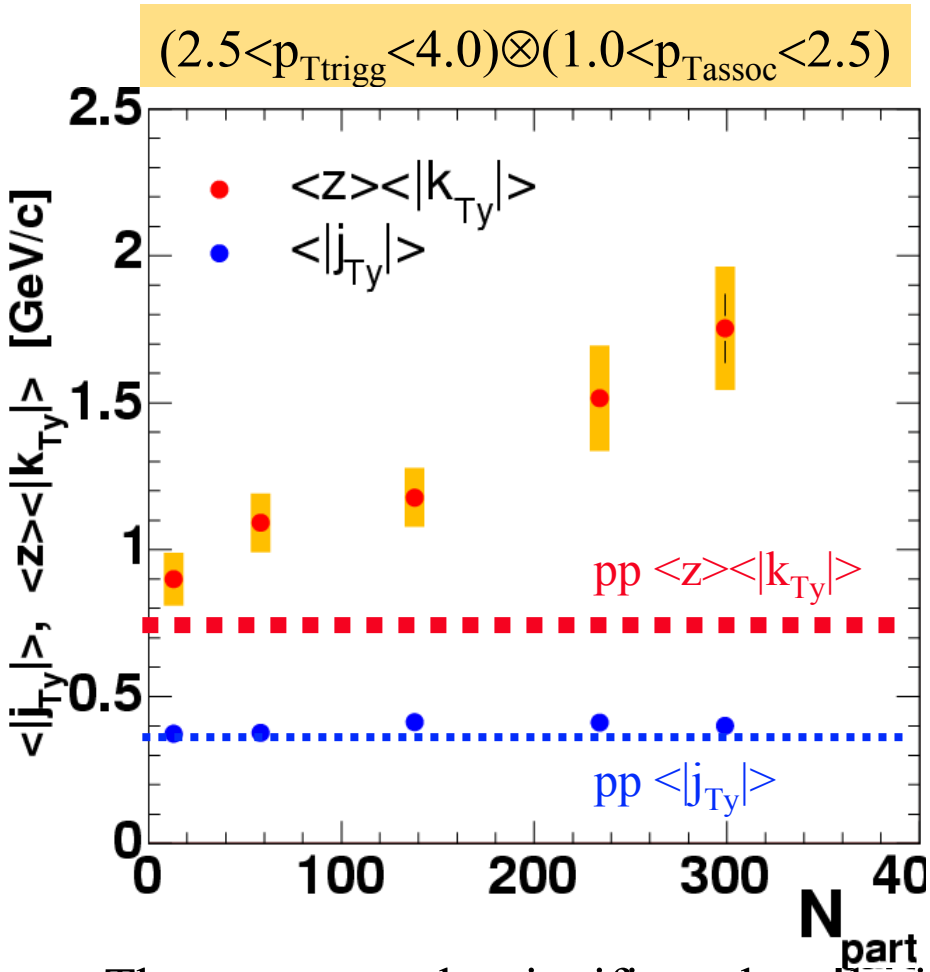


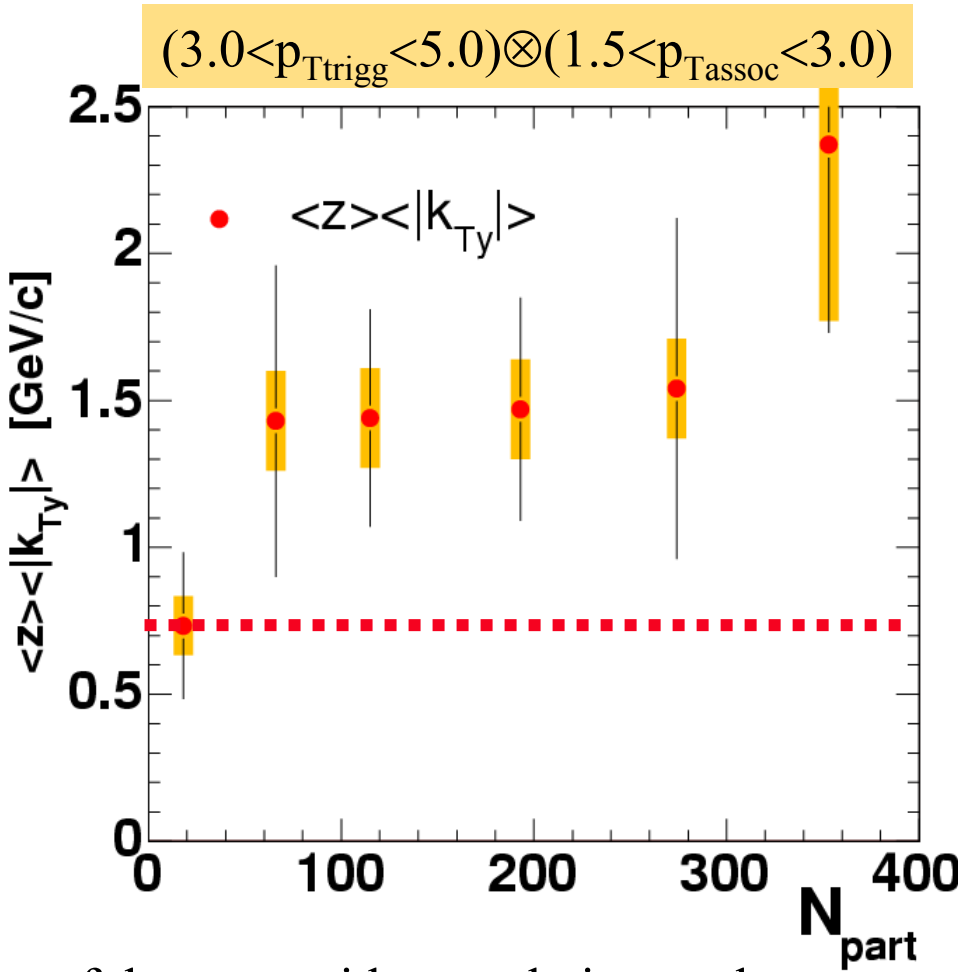
AuAu $\langle|j_{Ty}|\rangle$ and $\langle z\rangle\langle|k_{Ty}|\rangle$ from CF

Jana Bielcikova

Phys.Rev.Lett.92:032301,2004

$$\langle k_\perp^2\rangle_{AA} = \langle k_\perp^2\rangle_{vac} + \langle k_\perp^2\rangle_{IS\ nucl} + \langle k_\perp^2\rangle_{FS\ nucl}$$

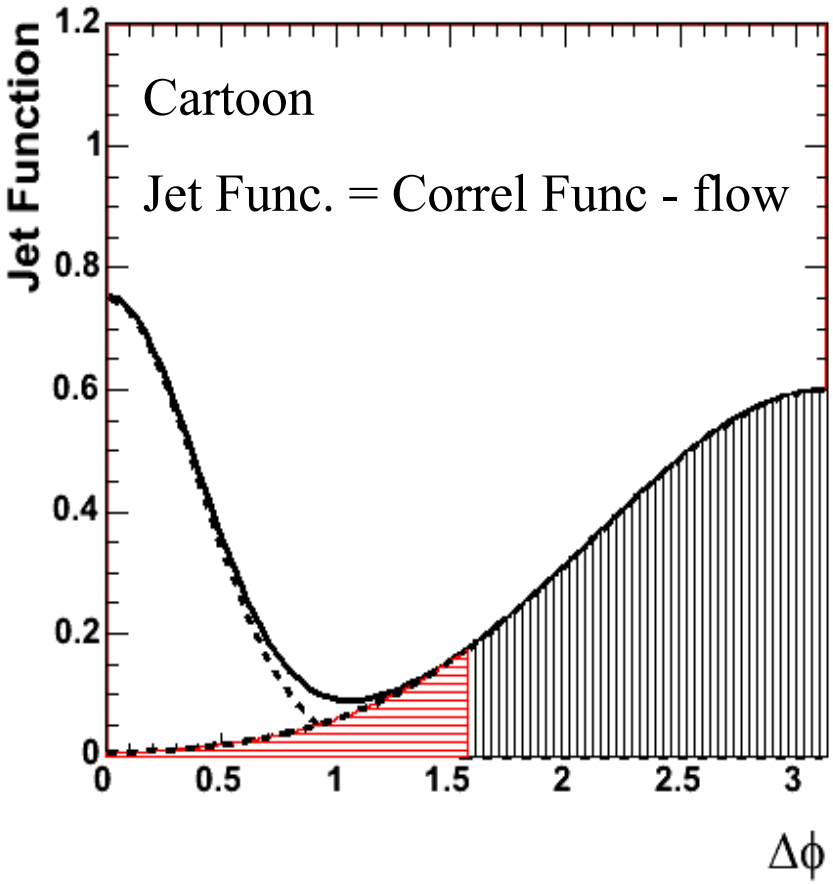


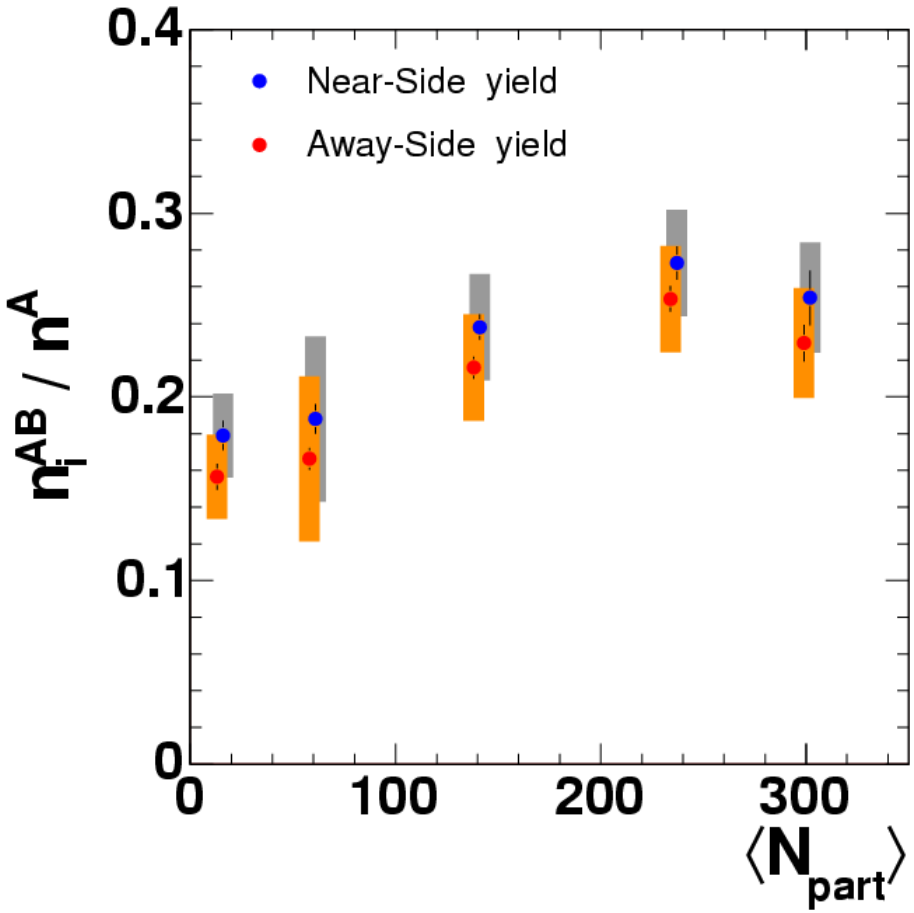


There seems to be significant broadening of the away-side correlation peak which persists also at somewhat higher p_T range.

AuAu associated yields

$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ GeV/c



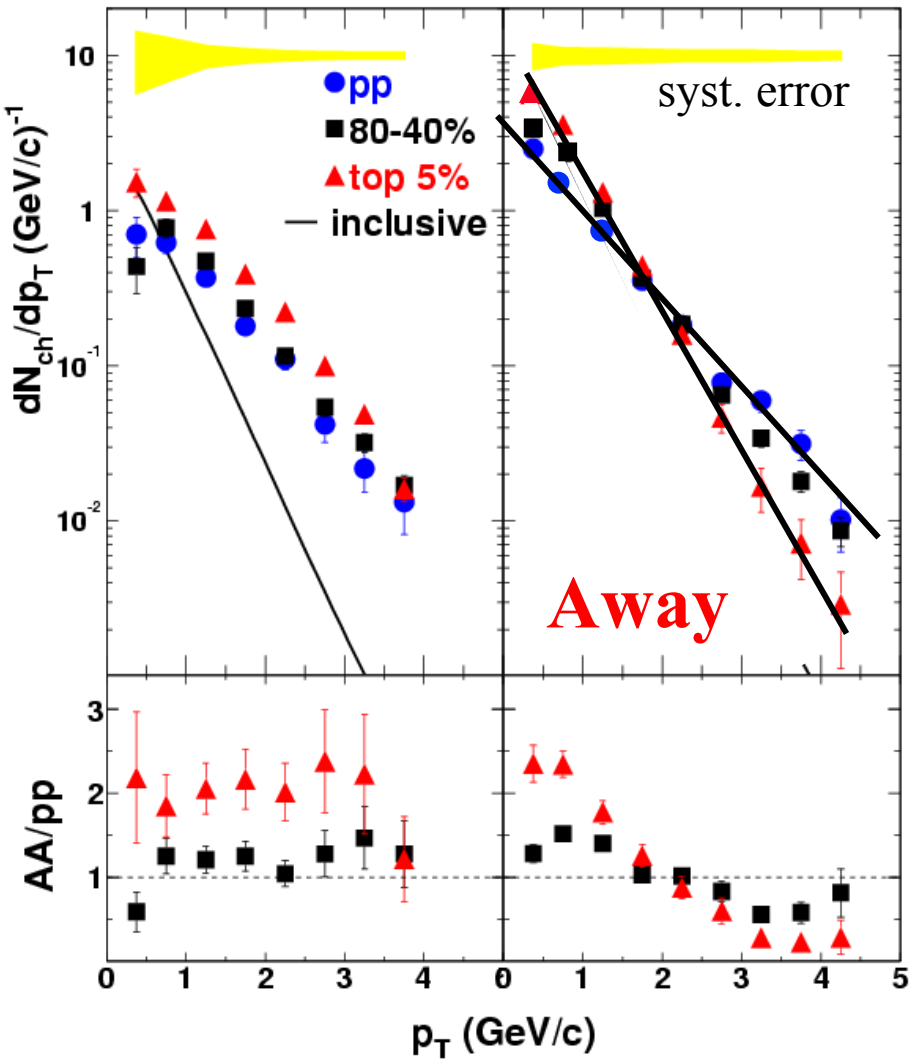


Note p_T is rather low; associated particle yields increase with centrality

p_T distributions on near and away side

Near side:

Overall enhancement from pp to AA



Away side:

energy from initial parton seems to be converted to lower p_T particles

reminiscent of energy loss predictions

Apparent modification of the fragmentation function ?

Summary and conclusions

Jet production and fragmentation:

- Good agreement of the jet properties in pp collisions with other lower $\sqrt{s}$ experiments
- dAu j_T and k_T consistent with pp
- In AuAu significant broadening of "effective" k_T - with centrality
- Yield of away side associated particles is suppressed at p_T>2GeV/c and shows rising trend with N_{part} below 2GeV/c. Remnant of high-p_T jets - hint of jet-quenching balance ?

SID'S